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SUPERLIGHT EXPANSION OF COMPACT RADIO SOURCES IN QUASARS

V. N. Kuril'chik*

The number one scientific sensation in observational radio astronomy in 1971 was the observation by American investigators of the expansion of the radio-variable structures of the quasars 3C 273 and 3C 279*** with speeds which greatly exceeded the light propagation speed (about 4 c and 6 - 10 c, respectively). The phenomenon became the subject of a lively discussion in scientific publications, and news of it spread in clamorous headlines in the newspapers of many countries of the world. /42**

It cannot be said that this discovery was completely unexpected for radio astronomers and astrophysicists. Already in 1969, on the basis of observations of the variation of the

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**Numbers in the margins indicate pagination in original foreign text.

***The nomenclature for the radio sources indicates that they are dimensions of the radiovariable structure of quasar 3C 273, a group of American radioastronomers made the preliminary conclusion that this structure may be expanding with a speed on the order of 2 c. However, only the independent investigations of several groups of radioastronomers carried out in 1971, and also subsequent investigations in 1972 - 1973, finally established the reality of this most interesting phenomenon. In particular, in addition to the two quasars mentioned above, the radio galaxy 3C 120, which shows a strong variability, displayed this effect (rate of apparent expansion of the variable radio source is about 2 c).

The latter circumstance is extremely important. It is thus possible to measure directly only the angular apparent rates of expansion of compact* variable radio structures. It is clear that in this case the linear speed of apparent expansion of the source in the figure plane (the plane perpendicular to the line of sight) depends on the distance from the investigated object, because it is directly proportional to the product of the angular speed of expansion and this distance. The rate of apparent linear expansion of radio sources in the quasars 3C 273 and 3C 279 was found with the assumption that their significant red shifts $z = \Delta\lambda/\lambda$, measured from optical emission lines, are cosmological in nature and, therefore, the distances to these quasars are of the order of billions of light years. However, the cosmological nature of the quasar red shifts is disputed by some authoritative Western astrophysicists, and thus the reality of the hyperlight expansion of the radio structures in these objects becomes doubtful. But in this respect, the radio galaxy 3C 120 is above all suspicion: the distance to it is well known. Thus, the reality of the phenomenon discussed here is confirmed, and a physical explanation of this phenomenon is required.

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registered in the review of the sky in the Third Cambridge Catalog, and that they have the corresponding ordinal numbers in that catalog.

*The term compact designates radiovariable structures with small angular ($\sim 10^{-3} - 10^{-4}$ seconds of arc) and physical ($\sim$ 1 - 10 parsecs) dimensions, as compared with much more extended stationary radio formations.

Let us recall that the observed translation rates — greater than the speed of light in vacuum, but not violating the laws of the theory of relativity — have been considered earlier. We shall dwell briefly on these ideas. /43

Hyperlight Speeds of Quasisources

The theory of relativity shows that a signal (energy, or mass, or information) cannot go from point to point with a speed greater than the speed of light. However, a motion not connected with the transfer of these quantities can take place with any speed. In 1943, I. M. Frank showed that the focal plane of a moving lens can move faster than the speed of light, and in 1971, B. M. Bolotovskiy and V. L. Ginsburg considered this same phenomenon for the motion of a light spot along a screen and for motion of the point of intersection of two straight lines.*

For simplicity, we shall give a concrete expression of these two experiments. Let some laser device rotate about its own axis with a frequency of 10^5 rotations per second (it is experimentally simpler, of course, to leave the laser device fixed and to rotate the laser beam from a rotating mirror). Let the laser be a pulsed device with a pulse duration of 10^{-12} seconds. Then little "chunks" of light of 0.3 mm total length will fly out from the laser. At a frequency of 10^{10} pulses per second, the distance between "chunks" of light is about 3 cm. But because the laser device is rotating, successively emitted "chunks" are arranged in space along a spiral (Figure 1). One after the other they will fall onto the screen. If the screen is located at a distance of 1 km (10^5 cm), the centers of "chunks" of light which are falling onto it will be positioned a distance of about 6 cm from each other, and the translation rate of the light spot along the screen will be $2\pi\, 10^5 \cdot 10^5 \simeq 6.3 \cdot 10^{10}$

*"Priroda", No. 4, 1972, p. 102.

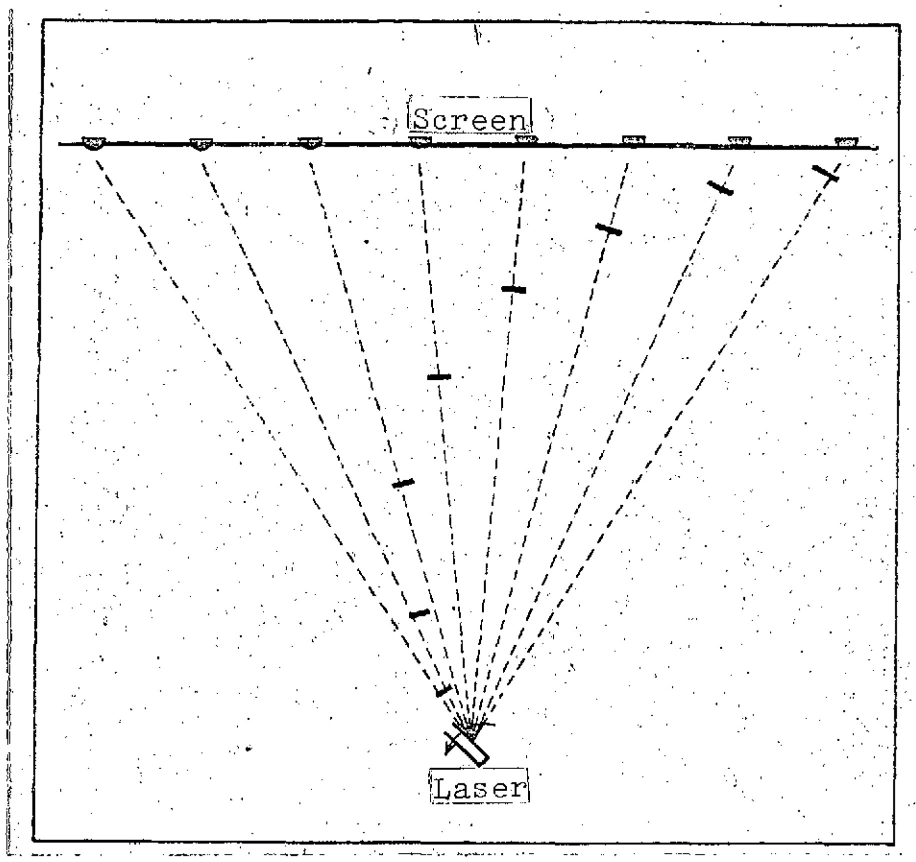

Figure 1. A light spot may move even faster than light. A rotating, pulsed laser emits individual portions of light which propagate always in a straight line along the indicated dashed trajectories with the speed c, while at the same time, the translational speed of the light spot along the screen will equal $2\pi Rn$, where R is the distance from the source of light to the screen, and n is the number of rotations of the light source per second. It is easy to give values of R and n such that the speed of the light spot is greater than the speed of light

cm/sec, i.e., more than twice the speed of light. Thus, the motion of light along the dotted trajectories, shown in Figure 1, carrying a real signal takes place with a lower speed than motion of the spot along the screen, which carries nothing from one point of the screen to another.

Now let us calculate the speed of the point 0, the point of intersection of two straight lines (Figure 2). Let a movable blade, inclined at an angle ϕ with respect to a motionless blade, fall downward with velocity v. Then during the time in which the movable blade goes through a distance AB, the point of intersection O will pass through a distance OB with velocity v'. Thus, $v' = vOB/AB = v\,\mathrm{ctg}\,\phi$. Let us recall that as ϕ approaches zero, ctg ϕ approaches infinity. Consequently, for sufficiently small ϕ, the translation rate of the intersection point can become arbitrarily large.

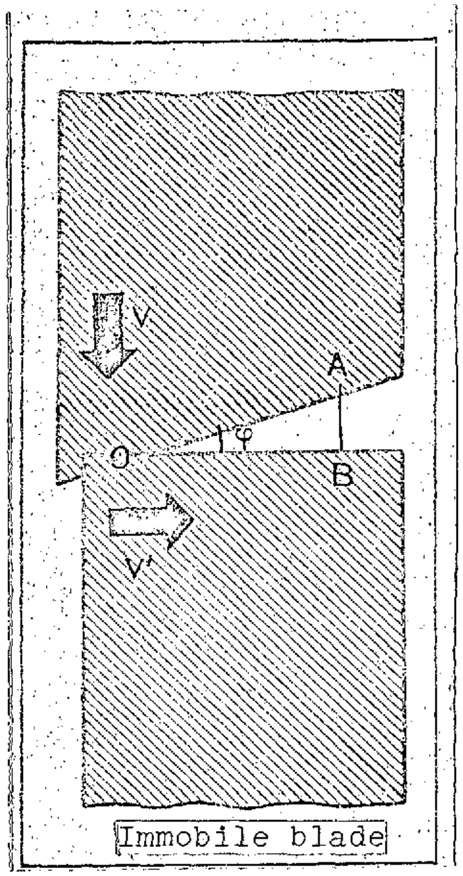

Figure 2. The intersection point of two straight lines can also move faster than light. Let a movable blade /44
inclined at an angle ϕ with respect to a stationary blade fall with a speed v. Then the speed v' of the intersection point from the triangle OAB will equal $v\,\mathrm{ctg}\,\phi$, and as $\phi \to 0$, it will approach infinity

We could analyze several more examples, but these are sufficient to clearly understand in which cases the speed of light is not an upper limit. But the sensation in the observation of quasars lies in the fact that radio-emitting substances are involved. It is easy to show that here, also, the rules of relativity are not violated.

Hyperlight Expansion of Real Sources

Our problem is to give an explanation of the hyperlight expansion of radiovariable sources. We judge the behavior of compact radiovariable sources by the information which we obtain in the form of their electromagnetic radiation (in the given case, it is radio frequency). Due to the finite propagation speed of radiofrequency radiation (the speed of light c is finite, and in vacuum it is constant), and since the radio source moves at a comparatively small angle with respect to the line of sight with a velocity of the order of the speed of light (during which the radiation source approaches the observer), the time interval for the reception by the observer of the radiation turns out to be significantly less than the corresponding time interval for the motion of the source. As a result, the real motion of the source (which cannot have a speed exceeding the speed of light) looks like hyperlight motion when its radio emission is observed. Generally speaking, this effect can exist also for any other form of signal, for example for sound, if the body which is emitting the sound moves with a speed somewhat less than, but sufficiently close to, the speed of sound, and if we judge the motion of the body on the basis of the sound information we have received.

Let a body which is continuously emitting a signal (the signal propagation speed is equal to c) move along a straight line at a constant velocity v, at some angle ϕ to the line of sight (Figure 3). While the body moves from some point 1 of its trajectory to point 2, i.e., traverses a distance $l = v \Delta t$, the signal emitted by it at point 1, moving toward the observer, traverses a

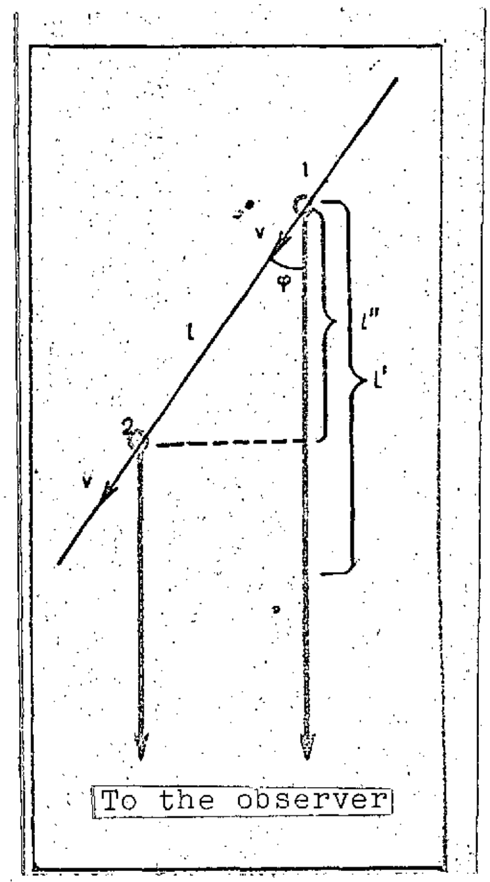

Figure 3. A sketch explaining the relationship between time intervals for the transit of a signal-emitting body and the time of reception of the signal by a distant observer. While the body traverses the path l from point 1 to point 2 at the speed v, the signal emitted at point 1 proceeds toward the observer along the path l', while the signal emitted at point 2 is displaced from it by a total of $l' - l''$; ϕ is the angle between the direction of motion of the body and the direction to the observer.

distance $l' = c\,\Delta t$ in this direction. During the same time, the body approaches toward the observer a distance $l'' = l \cos\phi = v\,\Delta t \cos\phi$, and, consequently, the signal emitted by it at point 2 lags behind in its motion toward the observer by a time:

$$\Delta t' = \frac{l' - l''}{c} = \frac{c\Delta t - v\Delta t \cos\varphi}{c} = \\ = \Delta t\left(1 - \frac{v}{c}\cos\varphi\right).$$

From the obtained relationship, it is evident that the time interval Δt for motion of the body from point 1 to point 2, generally speaking, is greater than the time interval $\Delta t'$, which it takes for the distant observer to receive the signal information about this motion. The greater the speed of the body (the closer it is to the speed of propagation c) and the smaller the angle ϕ, the greater will be the difference in these time intervals.

The real speed of the body in the figure plane $v_\perp = v \cdot \sin\varphi$. However, as a consequence of the fact that the signal information about this motion approaches the observer after a shorter time interval, the observed speed of the body in the figure plane $v_{\perp obs}$ is /45

$$\Delta t/\Delta t' = 1\Big/\left(1 - \frac{v}{c}\cos\varphi\right)$$

times larger. Then,

$$v_{\perp obs} = v_\perp\Big/\left(1 - \frac{v}{c}\cos\varphi\right) = \\ = \frac{v \sin\varphi}{1 - \frac{v}{c}\cos\varphi}$$

For a fixed, sufficiently small angle ϕ, the observed speed in the figure plane can be much larger than v, if v/c is close to unity, i.e., if the body moves at a speed which is comparable to the signal propagation speed. In particular, it may turn out that $v_{\perp obs}$ is greater than the speed of light, although in fact the emitting body moves with a smaller speed.

What Takes Place in a Quasar?

There is evidently a close connection between hyperlight expansion of compact radio sources close to the nuclei of quasars and of some radio galaxies with the phenomenon of the rapid and significant variability of radio emission of a whole series of quasars and some very active radio galaxies, which has been known since 1965. Quasars 3C 273, 279, and radio galaxy 3C 120 are rather typical representatives of this interesting category of radio sources, the number of which already reaches several hundred. It must be noted that the study of the variability of radio emission of extragalactic objects began with the discovery in 1965 by the Soviet radioastronomer B. G. Sholomitskiy of the variation of the object CTA 102*, which was identified somewhat later with a rather distant quasar.

The author of the present article, beginning in 1971, developed a new theoretical model of radiovariability, the essence of which is given in the following.

Strong arguments can be based on observational data in favor of the theory that magnetoplasma nuclei of quasars and galaxies have characteristic magnetic fields of a bipolar (for example, dipolar) character, the field lines of which extend out from two opposing poles, gradually widening at significant distances from the nuclei (possibly, right up to the components of binary radio structures, which are rather widespread among the extragalactic radio sources). Relativistic particles, including electrons, "flow out" from the poles of the magnetic field of an active nucleus, which serves as a continuous generator of cosmic rays. The electrons are responsible for the synchrotron radio frequency radiation of compact radio structures close to the nuclei. Through some internal mechanisms, the "outflow" of relativistic particles from the nuclei is not stationary; in the flux of particles there exist bunches (separate

*The nomenclature of the object implies that it is registered in the California Institute of Technology catalog in list A, with number 102.

clusters) of electrons, which cause more or less well defined bursts of radio emission following continuously, one after another. An individual cluster of relativistic electrons will, in the process of their anisotropic motion (along the field toward the periphery), expand according to the same law as that which governs the expansion with distance from the nucleus of the magnetic field tube. Each individual electron moves along its own axial field line in a spiral trajectory. The magnetic field is presumably sufficiently strong ($H \sim 10^{-1} - 10^{-2}$ Oe, which is substantiated by the detection of a significant circular polarization of the radio emission of the variable radio sources) so that it completely controls the motion of the relativistic particles in it. /46

Let us now turn directly to a phenomenon which interests us, the synchrotron emission of a cluster of relativistic electrons, which moves in a tube of a magnetic field oriented in space at a sufficiently small angle ϕ_H to the line of sight (Figure 4). For simplicity, we shall consider a tube of a field of uniform strengh H (not expanding) and, although of a finite length, nevertheless sufficiently distant from the observer so as to be visible at a small solid angle. In synchrotron radio emission, a relativistic electron moving, in the most general case, in a spiral trajectory along the magnetic field force lines with translational velocity along the line of sight $v_{\parallel} = v \cos \varphi \approx c \cos \varphi$ (where ϕ is the angle between the direction of the instantaneous velocity of the electron $\vec{v}$ and the direction of the field), continuously emits electromagnetic waves in the direction of its instantaneous velocity $\vec{v}$ in a rather narrow cone

$$\psi \simeq m_e c^2/E = \sqrt{1 - v^2/c^2}$$

(Figure 5). For an observer, the radiation of an individual electron is a train of pulses (the electron velocity $\vec{v}$ is oriented toward the observer, for example, at the points 1, 2, 3, etc., in Figure 5). The pulsed character of the electron emission is not so important to us here, as the fact that in the case of a cluster of electrons, only those electrons which are moving along the field at

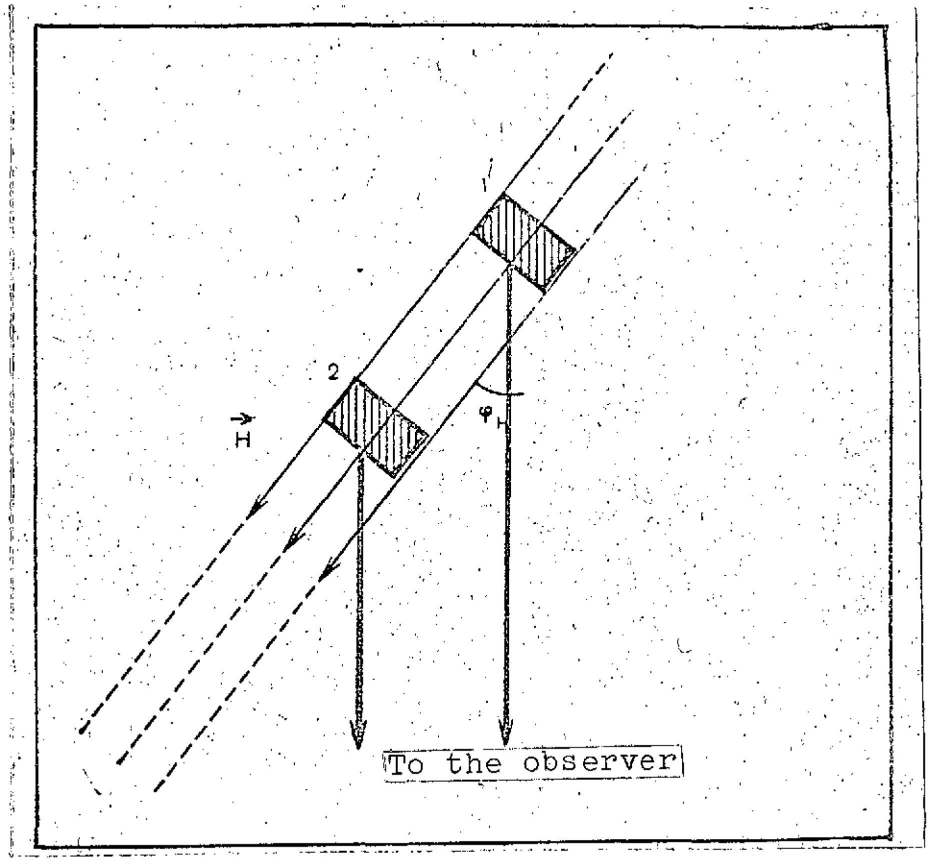

Figure 4. Geometry of a model of a cluster of relativistic electrons moving in a magnetic field tube. The shaded areas are regions in which electrons are localized and emitting toward the observer at certain moments during ther motion. $\vec{H}$ is the magnetic field, and ϕ_H is the angle between the direction of the magnetic field and the direction toward the observer

a definite angle $\varphi \simeq \varphi_H$ emit toward the observer (see Figure 4). Electrons moving at angles with respect to the field which differ from ϕ_H emit in other directions past the fixed direction to the observer. This allows us to determine the translational velocity along the field tube of those electrons which are emitting toward the observer. It is completely determined by its spatial orientation, and is equal to $v_{\parallel} \simeq c \cos \varphi_H$. This velocity also characterizes the translation rate of the radio source along the field tube.

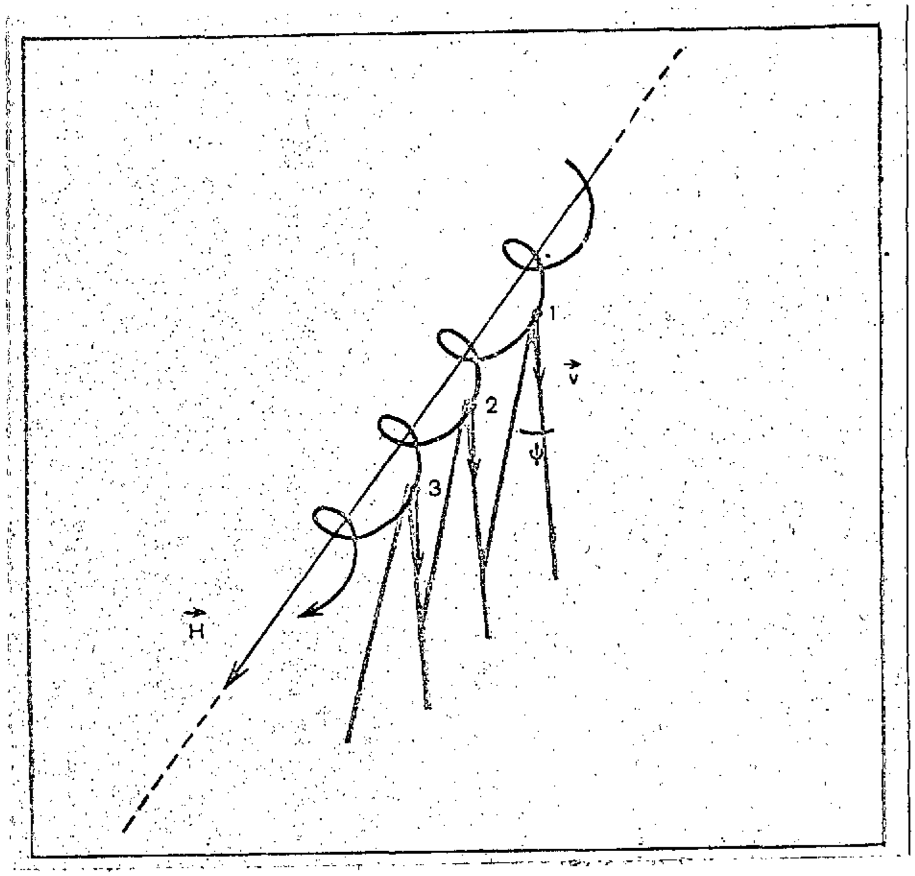

Figure 5. A sketch which explains the features of motion and emission of a relativistic electron in a magnetic field. An electron rotating around the force line of the magnetic field $\vec{H}$ emits electromagnetic waves in a narrow cone with aperture angle $\psi = m_e c^2/E$ in the direction of its instantaneous velocity $\vec{v}$. At points 1, 2, and 3, this velocity coincides with the direction to the observer

Substituting this velocity into the expression for the apparent (observable) velocity of the radio source in the figure plane, and taking into account the fact that $\varphi = \varphi_H$, we have:

$$v_{\perp obs} = c \cot \varphi_H.$$

From this expression, it follows that the rate of apparent motion of the radio emission source in the figure plane is larger, the smaller the angle ϕ_H is, i.e., it depends on the orientation of the /47 field tube in space. For all angles $\phi_H < 45°$, this speed is larger than the speed of light.

The considerations presented above for the simplest case of a uniform-strength magnetic field tube already enable us, in principle, to explain the observed effect of hyperlight expansion of compact variable radio structures, if by this we understand the relative motion of several radio sources in different field tubes (with different ϕ_H) with respect to each other, or of one such emission source with respect to some motionless radio emission center (for example, a source connected directly with the nucleus of a quasar or a galaxy).

The features of variable radio emission which are actually being observed can be explained, however, only in the case of a field tube which expands with the distance from the nucleus. The picture of the motion of the relativistic electrons in this case is more complex. Neglecting fine points, it can be shown that in the case of an expanding field tube, a separately chosen radio source (an individual cluster of electrons) exhibits hyperlight speed in apparent expansion.

Both the first investigations in the apparent variations in the structure of compact radiovariable sources and subsequent investigations of them indicate that most probably hyperlight divergence of two sources with respect to each other is being observed. In any case, such a model always figures in the interpretation of the phenomenon. One of the sources, in our opinion, is without doubt a moving cluster of electrons. The other is probably a motionless, compact region of radio emission, caused by a stationary (or quasi-stationary) electron flux in the same field tube of somewhat larger cross section. A stationary electron flux forms a bright, motionless region of radio emission at some distance from the nucleus (a region where the optical thickness with respect to cynchrotron self-absorption is approximately unity). Relative to this region, there takes place, evidently, motions of the sources, which are caused by individual denser clusters of relativistic electrons (Figure 6).

The divergence of a pair of radio sources is observed (the immobility of one of these is difficult to establish, because for this their coordinates must be measured with the highest accuracy, to ten-thousandths of a second of arc, which is impossible at the present time). However, it is not difficult to check the dynamics of this divergence by another observational method, upon which we shall not dwell.

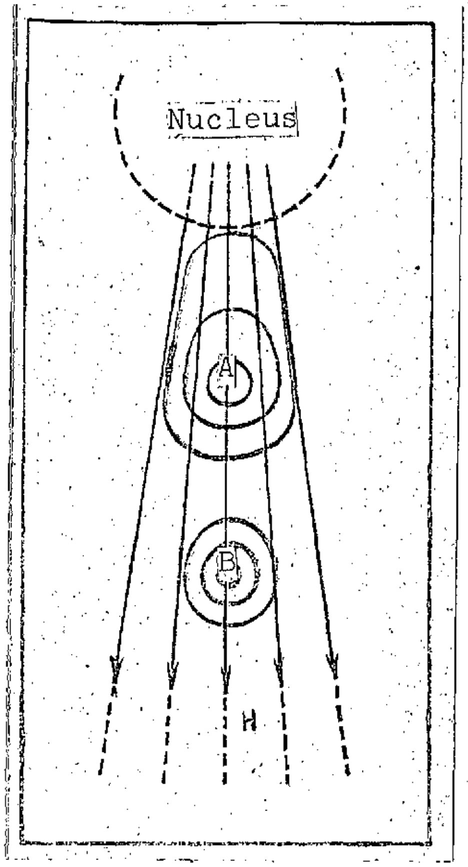

Figure 6. Proposed picture for the apparent divergence of pairs of radio sources. A — a motionless radio source; B — a moving radio source, H — the magnetic field

In support of the mechanism discussed for the phenomenon of raviovariability as a whole, and, in particular, in support of the explanation of the apparent hyperlight effect in the motion (expansion) of radiovariable structures, we present one important piece of observational evidence.

It is clear from the model which was considered that the apparent hyperlight expansion must take place in the figure plane in a direction which strictly corresponds to the direction of the projection of the magnetic field onto this plane. For a number of radiovariable sources, observations have revealed an astonishing feature: in every specific object, the vector E of the polarized radiation preserves, on the average, its quite definite position angle (direction in the figure plane). Comparing the position angles of the vector $\vec{E}$ (they must be perpendicular to the direction of the magnetic field) with the position angles at which the apparent hyperlight expansion of radiovariable sources takes place in every specific object, it is possible to verify our hypothesis. According, for example, to data of a recently published article [1], in quasars 3C 273 and 3C 279 and in the radio galaxy 3C 120, the vector $\vec{E}$ is oriented at position angles 141° ± 3°, 137° ± 5°, and 176° ± 3°, respectively. From this, we obtain for the position angles of the direction of the magnetic field the values 51° ± 3°, 47° ±5°, and 86° ± 3°, respectively. The hyperlight expansion of the variable radio sources takes place in 3C 273 at a position angle [2] 60° ± 10°, in 3C 279 at a position angle [3] of 43° ± 5°, and, finally, in 3C 120 at a position angle of 85° ± 5°. Commentary, as they say in such cases, is superfluous.

In conclusion, let us note that the features of radiovariable radiation in all its aspects will very likely enable us in the very near future to clarify the physical picture of the complex phenomena both around and in the active nuclei of galaxies and quasars, and will, in particular, enable us to study the character of the magnetic field structure of the nuclei, which is extremely important for our understanding of the structure of the nuclei as a whole.

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